NUMERICAL AND EXPERIMENTAL INVESTIGATIONS ON TEMPERATURE AND THERMAL DAMAGE IN CORTICAL BONE DRILLING

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Doctor of Philosophy

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SUPERVISOR’S DECLARATION

I hereby declare that I have checked this thesis and in my opinion, this thesis is adequate in terms of scope and quality for the award of the degree of Doctor of Philosophy.

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STUDENT'S DECLARATION

I hereby declare that the work in this thesis is based on my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for any other degree at Universiti Malaysia Pahang or any other institutions.

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"One who treads a path in search of knowledge has his path to Paradise made easy by Allah"
Muhammad Bin Abdullah (PBUH) – Riyadh us Solihin, 245.

ABSTRAK

Penggerudian tulang adalah operasi yang biasa dalam pelbagai jenis pembedahan dalam *orthopedics*, *oral and maxillofacial*, *neurological*, dan *otolaryngology*. Tenaga geseran dan ricih semasa pembedahan menghasilkan haba yang tinggi, yang mana akan meningkatan suhu tulang. Tambahan pula, kekonduksian haba yang rendah oleh tulang meningkatkan lagi suhu tulang dan menyebabkan kematian sel-sel tulang (*thermal osteonecrosis*). *Thermal osteonecrosis* melonggarkan penetap tulang patah (*orthopedics*), implant gigi (*oral and maxillofacial*), dan implant koklea (*otolaryngology*), yang mana boleh menyebabkan pembedahan berulang. Pembedahan ini memerlukan kos tambahan dan masa penyembuhan yang lama. Yang lebih membimbangkan, *thermal osteonecrosis* boleh menyebabkan kecacatan kekal kepada pesakit apabila ia melibatkan kecederaan saraf. Parameter penggerudian (halaju putaran, suapan, kedalaman lubang, dan diameter mata gerudi) dan geometri mata gerudi (sudut mata, sudut *helix*, dan ketebalan web) telah dikenalpasti sebagai sebagai dua faktor yang bole dimanipulasi untuk mengurangkan suhu tulang. Oleh itu, tesis ini mensasarkan untuk mengurangkan kerosakan haba semasa penggerudian tulang dengan menggunakan parameter penggerudian optimum (ODP) dan geometri mata gerudi yang ditambahbaik (IDG). Untuk menentukan ODP dan IDG, pendekatan *numerical*, *experimental* dan *statistical* telah digunakan. Model tulang kortikal manusia dan mata gerudi telah dihasilkan menggunakan perisian *finite element method* (FEM), DEFORM-3D. Untuk parameter penggerudian, halaju putaran dari 50 rev/min sehingga 400,000 rev/min, suapan dari 0.0100 mm/rev sehingga 0.1875 mm/rev, kedalaman lubang dari 0.5 mm sehingga 5.0 mm, dan diameter mata gerudi dari 0.5 mm sehingga 6.0 mm telah dikaji. Untuk geometri mata gerudi, sudut mata 60–160°, sudut *helix* 10–36°, dan ketebalan web 5–50 % telah dikaji. Hasil simulasi telah disahkan dengan penggerudian tulang secara *experimental* menggunakan *conventional milling machine*. Kaedah baru yang dinamakan jumlah pemberat telah diperkenalkan untuk menentukan julat yang sesuai untuk kajian pengoptimuman. Dari hasil jumlah pemberat, julat untuk parameter penggerudian (halaju putaran = 50–500 rev/min dan suapan = 0.1600–0.1875 mm/rev) dan geometri mata gerudi (sudut mata = 118°–140°, sudut *helix* = 30°-36°, dan ketebalan web = 10 %–18 %) telah dipilih. Kaedah *response surface methodology* (RSM) dan pengoptimuman pelbagai objektif telah dilakukan untuk menentukan ODP dan IDG. Hasil kajian mendapati ODP boleh dihasilkan dengan halaju putaran 50 rev/min dan suapan 0.1750 mm/rev. Mata gerudi pembedahan yang optimum (*stainless steel 316L*) boleh dihasilkan dengan sudut mata 131.8°, sudut *helix* 36°, dan ketebalan web 11.8 %. ODP yang dicadangkan boleh mengurangkan kerosakan haba dengan ketara sekali berbanding dengan cadangan daripada kajian-kajian lepas (kenaikan suhu tulang maksimum (T_{max}) = 8.9–85.8 °C, diameter osteonecrosis (OD) = 5.16 mm–10.07 mm, dan kedalaman osteonecrosis (OH) = 3.35–5.50 mm). Selain itu, IDG dapat mengurangkan kerosakan haba melebihi mata gerudi pembedahan yang sedia ada (T_{max} = 2.3 °C, OD = 1.16 mm, and OH = 1.96 mm). Apabila ODP dan IDG digabungkan secara serentak, kerosakan haba dapat dikurangkan lagi sehingga 1.2 °C ke 9.3 °C untuk T_{max}, 4.45 mm untuk OD, dan 2.22 mm untuk OH daripada menggunakan ODP dan IDG. Sumbangan asli daripada tesis ini boleh didapati daripada beberapa bahagian. Kajian ini telah menentukan model tulang yang sesuai untuk menggantikan tulang manusia (dari segi kenaikan suhu tulang). Selepas itu, ODP dan IDG baru telah dicadangkan untuk mengurangkan kerosakan haba. Kajian in telah menambahkan pengetahuan kita tentang pencegahan osteonecrosis haba dan boleh dijadikan sebagai asas untuk kajian masa hadapan dalam penggerudian tulang secara automasi.

ABSTRACT

Bone drilling is a typical operation in the myriad of surgeries in the orthopedics, oral and maxillofacial, neurological, and otolaryngology. Friction and shear deformation energy during the drilling surgery generates extreme heat in the drilling hole, which increases the bone temperature. Furthermore, the low thermal conductivity of bone escalates the bone temperature and causes the irreversible death of the bone cells (thermal osteonecrosis). Thermal osteonecrosis loosens fracture fixations (orthopedic), tooth implants (oral and maxillofacial), and cochlear implants (otolaryngology), which could cause revision surgeries. These surgeries necessitate additional costs and healing time. Moreover, to add insult to injury, thermal osteonecrosis could even cause permanent disability to the patients when it involves nerve injuries. Drilling parameters (rotational speed, feed, drilling hole depth, and drill bit diameter) and drill bit geometries (point angle, helix angle, and web thickness) have been identified as two main factors that can be manipulated to reduce the bone temperature. Therefore, this thesis aims at reducing the thermal damage in bone drilling by using optimal drilling parameters (ODP) and improved drill bit geometries (IDG). In order to determine the ODP and IDG, approaches including numerical, experimental, and statistical were adopted. Human cortical bone and surgical drill bit models were developed using commercially available finite element method (FEM) software, DEFORM-3D. In terms of drilling parameters, the rotational speed of 50 rev/min to 400,000 rev/min, feed of 0.0100 mm/rev to 0.1875 mm/rev, drilling hole depth of 0.5 mm to 5.0 mm, and drill bit diameter of 0.5 mm to 6.0 mm were investigated. Whereas, for drill bit geometries, the point angle of 60-160°, helix angle of 10-36°, and web thickness of 5-50 % were investigated. The simulation results were validated then with the experimental bone drilling using a conventional milling machine. A new method called sum of weightage was introduced to determine the suitable ranges for optimization study. From the sum of weightage results, the ranges for drilling parameters (rotational speed = 50-500 rev/min and feed = 0.1600-0.1875 mm/rev) and drill bit geometries (point angle = 118°-140°, helix angle = 30°-36°, and web thickness of 10 %-18 %.) for optimization study were selected. Then, the response surface methodology (RSM) and multi-objective optimization studies were performed to determine the ODP and IDG. Results revealed that the ODP could be obtained with a rotational speed of 50 rev/min and feed of 0.1750 mm/rev. Whereas, the optimal surgical drill bit (stainless steel 316L) can be constructed with a point angle of 131.8°, helix angle of 36°, and a web thickness of 11.8 %. The proposed ODP can significantly reduce the thermal damage compared with the recommendations from the previous studies (maximum bone temperature elevation (T_{max}) = 8.9–85.8 °C, osteonecrosis diameter (OD) = 5.16 mm-10.07 mm, and osteonecrosis depth (OH) = 3.35-5.50 mm). Furthermore, the IDG can reduce thermal damage more than the existing surgical drill bit (T_{max} = 2.3 °C, OD = 1.16 mm, and OH = 1.96 mm). When ODP and IDG are combined, the thermal damage can further be reduced up to 1.2 °C to 9.3 °C for T_{max}, 4.45 mm for OD, and 2.22 mm for OH compared with when using ODP and IDG individually. The significant original contributions from this thesis come from several areas. This work has determined the suitable bone model as the replacement for human bone in bone drilling (in terms of temperature elevation). Next, new ODP and IDG were recommended to reduce significant thermal damage. This research extends our knowledge of thermal osteonecrosis prevention and will serve as a base for future studies in the automation of bone drilling surgery.

TABLE OF CONTENT

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS

c	Coefficient
D	Critical Damage
d_i	Individual Desirability
F_{LOF}	F-value for Lack-of-Fit
$High_i$	Higher Acceptable Value
j	Shear Stress
k	Number of Factors
Low_i	Lower Acceptable Value
m	Coefficient
MS_{LOF}	Mean Square for Lack-of-Fit
MS_{PE}	Mean Square for Pure Error.
n	Coefficient
N	Number of Experiments
nc	Number of Center Point
nf	Number of Factorial Point
OD_{high}	Highest Measured OD
OD_i	Measured OD Value for Each Drilling Parameter
OD_{low}	Lowest Measured OD
OH_{high}	Highest Measured OH
OH_i	Measured OH Value for Each Drilling Parameter
OH_{low}	Lowest Measured OH
r	Coefficient
s	Shear Friction Factor
T	Temperature
T_0	Ambient Temperature
T_i	Target Value
T_{max}	Maximum Bone Temperature Elevation
$T_{max_{high}}$	Highest Measured T_{max}
T_{max_i}	Measured T_{max} Value for Each Drilling Parameter
$T_{max_{low}}$	Lowest Measured T_{max}
W_i	Sum of Weightage for Each Drilling Parameter

W_{OD}	Weightage of OD
W_{OH}	Weightage of OH
wt_i	Weight for the Target Value
W_{Tmax}	Weightage of T_{max}
X_1	Statistical Factor 1
X_2	Statistical Factor 2
X_i	Statistical Factors
y	Coefficient
Y	Response Variable
Y_i	Particular Response
α	Axial Distance in CCD
$\bar{\sigma}$	Effective Flow Stress
ε_{eff}	Effective Fracture Strain
$\bar{\varepsilon}$	Effective Plastic Strain
$\dot{\bar{\varepsilon}}$	Effective Strain Rate
σ_{eff}	Effective Stress
α	Factorial Point
σ_{max}	Maximum Stress
ε_p	Plastic Strain
$\dot{\varepsilon}_p$	Plastic Strain Rate
τ	Shear Friction
β_0	Statistical Constant
β_i	Statistical Constant
β_{ij}	Statistical Constant
β_1	Statistical Constant
β_2	Statistical Constant
ε	Statistical Error
$d\bar{\varepsilon}$	Strain Increment
σ	Stress

LIST OF ABBREVIATIONS

ANOVA	Analysis of Variance
ASTM	American Society for Testing and Materials
CCD	Central Composite Design
df	Degrees of Freedom
DOE	Design of Experiment
EXP	Experiment
F	Force
FEA	Finite Element Analysis
FEM	Finite Element Method
GDP	Gross Domestic Product
HSS	High-Speed Steel
IDG	Improved Drill Bit Geometries
K	Number of Treatments
L	Lack-of-fit Score
M	Sequential Model Sum of Squares Score
N	Total Number of Observations
OD	Osteonecrosis Diameter
ODP	Optimal Drilling Parameters
OH	Osteonecrosis Depth
PMMA	Polymethyl Methacrylate
RSM	Response Surface Methodology
SEM	Scanning Electron Microscope
SSE	Sum of Squares Error
SSR	Sum of Squares Regression
SST	Sum of Squares Total
T	Temperature
To	Torque
USD	United States Dollar

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